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A Novel Dualband Coaxial-fed SIW Cavity Resonator Antenna using ANN Modeling

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Abstract

Substrate Integrated Waveguide (SIW) presents a promising technology to realize planar antennas, due to its ability to render the advantages of conventional rectangular waveguides, such as low radiation losses, high quality factors, and high power handling capabilities. Artificial Neural Network (ANN) presents also a relevant optimization technique widely used for the modeling of antenna design problems to obtain a surrogate based model instead of a computationally intensive three dimensional electromagnetic (3D EM) simulation in design. Accordingly, this paper proposes for X (8-12 GHZ) and Ku (12-18 GHz) microwave spectrum; a novel design of dualband coaxial-fed antenna, using a microwave SIW cavity resonator to ensure operational frequencies for different kind of purposes, and structured supervised learning alternative to neural networks to provide accurate geometric dimensions for the target requirements. A prior knowledge about the antenna design problem such as an empirical formula, an equivalent circuit model, and an analytical equation, is directly embedded in ANN structure to improve some properties of conventional modeling such as accuracy and data requirement, and exhibit an ideal frequency response and satisfies the design specifications after six iterations. The antenna is found to resonate at 10.84 GHz and 14.82 GHz respectively, and show low return losses of less than -15dB to -30dB for the selective frequency bands, resulting in excellent performance, and good agreement between the simulated results of the optimized antenna dimensions and the target results initially selected for the antenna role.

Keywords: SIW antennas, CPW feeding, Cavity Resonator, X and Ku bands, ANN Modeling.

1. Introduction

Substrate integrated waveguide technology has been recently exploited in providing a variety of compact low-loss integrated systems, and realizing several passive and active devices at the frequency of microwave and millimeter waves [1, 2]. It has motivated a fast expansion of different applications operating at high frequencies by implementing periodic metallic via holes to largely preserve the advantages of conventional rectangular waveguides and microstrip lines, such as high quality factor, high power capacity, self-consistent electrical shielding, small volume, light weight, and simple transitions with the other components [3, 4].

In particular, antennas employing SIW resonators have achieved excellent properties such as good radiation, high gain, very wide bandwidth, and their difficult modeling into planar forms due to the bulky geometry, seems to become easier. SIW cavity resonators have been especially used in designing antennas for the accurate determination of the resonance frequency of the dominant mode [5]. This has consequently provided an important class of millimeter and microwave antennas with numerous wireless applications, considerably after having used advanced automatic modeling techniques to bring the Computer-Aided Tuning (CAT) for such high frequency structures to its current state of the art.

Artificial neural networks present one of the automation techniques used for modeling SIW antennas. They consist of information processing systems with their design inspired by the studies of the ability of the human brain to learn from observations and to generalize by abstraction [6, 7]. ANNs can be used to develop new models or enhance the accuracy of existing models. They learn device data through an automated training process, and the trained neural networks are then used as fast and accurate models for efficient high-level design.

In this paper, a novel design of a dualband coaxial-fed SIW cavity resonator antenna using High Frequency Structure Simulator (HFSS) is proposed for X (8–12 GHz) and Ku (12–18 GHz) band applications. The SIW cavity resonator antenna adopts two main parts: a tulip-shaped patch [8] and coaxial feeding line. The antenna parameters are optimized by developing an accurate MATLAB-based ANN model, trained by back-propagation technique as fitness function for excellent learning and accurate designingof the antenna geometric structure. ANN Algorithms are trained by a set of existent input and output relations obtained by simulation to test data for the algorithms and analyze the SIW antenna parameters for the selective bandwidth. The design is then validated by comparing the ANN responses with input values provided for the combinations of dimension values, within the parameter range of the test set.

2. SIW Cavity Resonator Antenna Design

The geometry of the proposed SIW antenna as shown in

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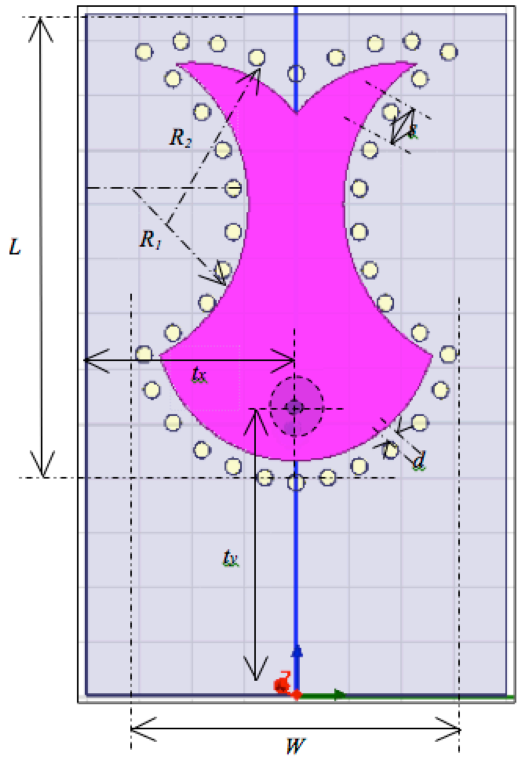
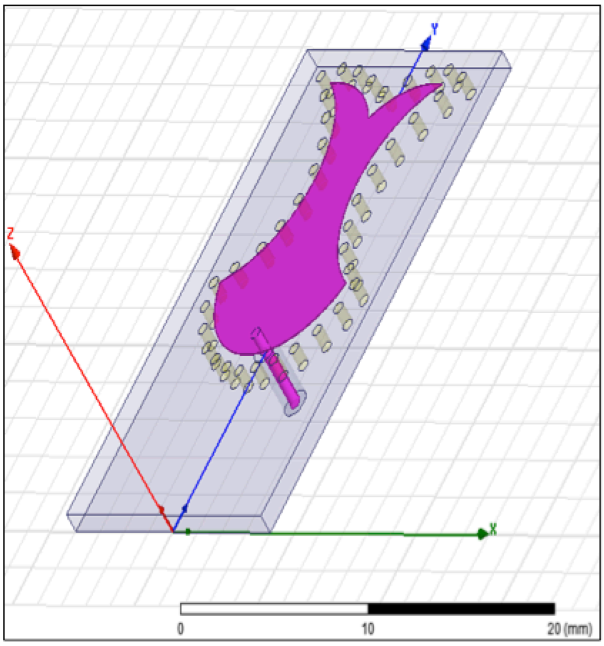
Figure 1, is mainly composed of walls presented by two rows of metalized via holes with center-to-center distance called (W_{SIW}), embedded into a dielectric substrate and by the top and the bottom metallization of the dielectric substrate.



(a)



(b)

Fig. 1. Layout (a) and three dimensional model (b) of the proposed dualband coaxial-fed SIW cavity resonator antenna in HFSS

The structure can be modeled by a conventional cylindrical cavity resonator, mainly defined by its horizontal length (W), vertical length (L) designed to determine the guide's cut-off frequency and modes of excitation. The diameter (d) and walls center-to-center distance (s) of via holes can be adjusted while maintaining the conditions of the set of equations (1) [9].

$$\begin{cases} d/s \leq 0.5 \\ d/\lambda_0 \leq 0.1 \end{cases} \quad (1)$$

To guarantee a minimum leakage of power through the sidewall of the cavity where (λ_0) denote free space wavelength. To design SIW resonance cavity, the dimensions can be chosen according to desired resonance frequency (f_{mnp}) of (T_{mnp}) mode that can be calculated according to [10]:

$$f_{mnp} = \frac{c}{2\pi\sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{P_{nm}}{R}\right)^2 + \left(\frac{p\pi}{h}\right)^2} \quad (2)$$

In which (R: R_1 or R_2) is the radius of the circular SIW cavity, (μ_r and ε_r) are relative permeability and permittivity of the filling material used for the cavity, and (m, n and p) refer to the numbers of variations in the standing wave pattern. The (P_{nm}) represents the corresponding root of Bessel function and (c) stands for light speed in free space. For the TM010 (P_{01} = 2.4049) and TM_{110} (P_{11} = 3.832) modes, the resonance frequencies are 10.8 GHz and 14.8 GHz, which belong to X band and K band of frequencies. Note that not every high-order mode can be excited to radiate, which depends on the positions and types of the feeding and radiator. A pseudo cylindrical cavity ($W*L$ = 12.2*16.4 mm^2) has been considered. Vias diameter is of (d = 0.6 mm) and their separation (center to center) is of (s = 0.8 mm). The layer between the conducting plates has a permittivity of (ε_r = 3.2), a tangent loss of (δ = 0.0018), and a thickness (h = 0.95 mm).

Accordingly, a set of antenna geometric specifications is proposed for the analysis and optimization, after having determining the SIW parameters, and calculating the remaining antenna parameters including both coaxial feeding and tulip patch parameters by using HFSS-based Eigen-mode solution. Details of geometric configuration of the dualband coaxial-fed SIW cavity resonator antenna proposed for the study, is illustrated in Table 1.

Table 1. Geometrical parameters of the proposed dualband coaxial-fed SIW cavity resonator antenna

<table>
<tr><th colspan="6">Parameters (mm)</th></tr>
<tr><th colspan="6">Cavity resonator</th></tr>
<tr><td colspan="2">Vertical length (L)</td><td colspan="2">Horizontal length (W)</td><td colspan="2">Thickness (h)</td></tr>
<tr><td colspan="2">16.4</td><td colspan="2">12.2</td><td colspan="2">0.95</td></tr>
<tr><th colspan="6">SIW</th></tr>
<tr><td colspan="3">Diameter (d)</td><td colspan="3">Walls Center-to-center distance (s)</td></tr>
<tr><td colspan="3">0.6</td><td colspan="3">0.8</td></tr>
<tr><th colspan="6">Tulip-shaped patch</th></tr>
<tr><td colspan="3">Inner ray (R_1)</td><td colspan="3">Outer ray (R_2)</td></tr>
<tr><td colspan="3">3.5</td><td colspan="3">4.5</td></tr>
<tr><th colspan="6">Coaxial feeding port</th></tr>
<tr><td colspan="3">Horizontal translation (t_x)</td><td colspan="3">Vertical translation (t_y)</td></tr>
<tr><td colspan="3">8.2</td><td colspan="3">10.2</td></tr>
</table>

3. Artificial Neural Network Modeling of the SIW cavity resonator antenna

Geometrical parameters of the proposed SIW antenna has been optimized by introducing an ANN model using

MATLAB programming [11], in order to enhance the accuracy of the existing structure through an automated data training process having the ability to capture multi-dimensional arbitrary nonlinear relationships in a very fast way to finally provide an efficient high-level antenna design.

In this work, a Multilayer Perceptron (MLP) network structure has been adopted for the calculation of the resonant frequencies and return losses using for training standard, back propagation algorithms [12, 13], in which neurons are grouped into three layers divided into: first layer which consists of input neurons, output layer which contains the output neurons, and remaining layer presenting the hidden layer.

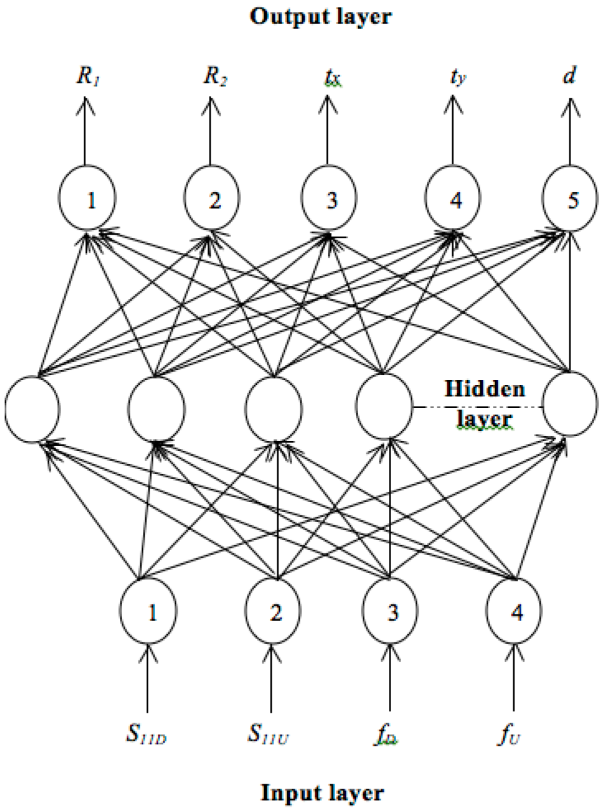


Fig. 2. MLP-ANN architecture selected for the optimization

Table 2. ANN parameters of the dualband coaxial-fed SIW cavity resonator antenna

Parameters	Optimized Values				
Training algorithm	Feed-forward MLP/ Backpropagation				
Number of neurons	Number of hidden neurons / Number of output neurons		4		5
	Number of hidden neurons		15		
Transfer function	Hidden levels		Sigmoïde		
	Hidden levels		Lineair		
Inputs definition		f_D (GHz)	S_{11D} (dB)	f_U (GHz)	S_{11U} (dB)
	Max	11.4	-25	14.4	-30
	Min	10.6	-30	15.2	-35
Learning rate	0.02				
The number of epochs	1000				

Figure 2 illustrates the MLP-ANN architecture used for the simulation and optimization. For the considered SIW antenna, the developed neural model is designed to produce output parameters divided into R_1, R_2, t_x, t_y and d, having down return loss S_{11D}, high return loss S_{11U}, down resonance frequency f_D and upper resonance frequency f_D as inputs. The neural network parameters used for the optimization are indicated in Table 2.

After having defined the antenna's input and output variables as a first stage known as neurons process, training data are generated using multi-HFSS simulations to provide a neural network model that will be incorporated into the simulator again for fast and accurate optimization as a second stage of the overall device called network training process. Likewise, the training error is automatically calculated, and network weights are being updated after each cycle in order to minimize the training error. The aim of the network training process is then to teach the network to produce valid response for inputs from outside the training data that is simply called generalization [14].

4. Optimization results and discussion

4.1. Optimization Procedure

Before starting the optimization process, the first step consists to determine an equivalent circuit presenting the antenna design parameters (X_{EM}), based on the multi-HFSS simulation results. Then, the optimization operation will be launched aiming to determine a new antenna configuration providing simulation results close to the target design specifications (X_{target}) initially proposed.

The key technique used in this adaptive CAT procedure is explained in details in Table 3 which summarizes the acceptable errors, and Figure 3 which presents the set of the design process steps.

Table 3. Adaptive CAT variables for the optimization process

Sr N°	ANN inputs			
	f_D (GHz)	$S_{11(D)}$ (dB)	f_U (GHz)	$S_{11(U)}$ (dB)
1	10.6	-31	14.2	-32
2	10.7	-33	14.4	-30
3	10.75	-30	14.7	-35
4	10.8	-35	14.8	-28
5	11	-25	14.98	-30
6	11.2	-30	15	-32

Sr N°	ANN outputs				
	R_1 (mm)	R_2 (mm)	t_x (mm)	t_y (mm)	d (mm)
1	4.999	6.149	7.989	9.998	0.280
2	5.201	6.334	8.235	9.093	0.387
3	5.193	6.608	8.242	10.207	0.246
4	4.991	6.299	8.223	9.227	0.522
5	5.199	6.532	9.452	9.213	0.489
6	5.221	6.511	9.603	9.622	0.501

Sr N°	HFSS outputs			
	f_D (GHz)	$S_{11(D)}$ (dB)	f_U (GHz)	$S_{11(U)}$ (dB)
1	10.4	-17.28	14	-13.86
2	10.5	-14.48	14.1	-16.65
3	10.5	-13.75	14.3	-15.98
4	10.6	-19.18	14.2	-13.67
5	10.7	-13.14	14.8	-15.27
6	10.84	-15.18	14.82	-29.83

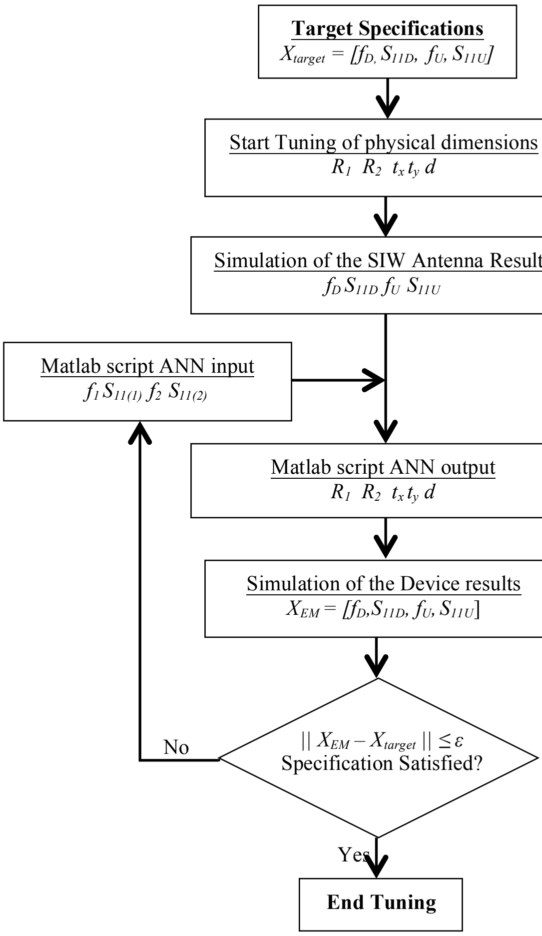


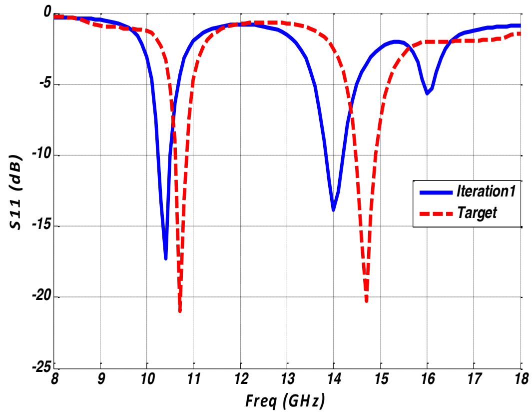
Fig.3. Adaptive CAT procedure for the optimization process

4.2. Simulated Return Losses

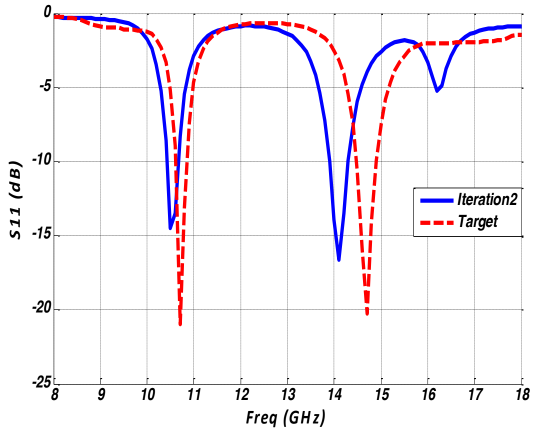
Parameters outputted by the trained ANN model have been implemented by HFSS software to compare the antenna response with the target response. Figure 4 (a to f) shows the simulated return losses of the antenna design, optimized using an accurate ANN model. It is clearly observed that the geometric configuration begins to provide low return losses from iteration to other that become very close to the target return losses in the sixth iteration. Figure (5-f) shows that the antenna structure comes with very low return losses over the entire bands of resonance. The antenna has been found to resonate at 10.84 GHz with a return loss of less than -15dB, and at 14.82 GHz with a return loss of less than -29dB. The values obtained from ANNs are very close to target values. The difference between the ANN outputs against target is measured in terms of performance which is very close to set goal to be achieved in testing for better performance of the network model.

4.3. Input Impedance And Radiation Pattern

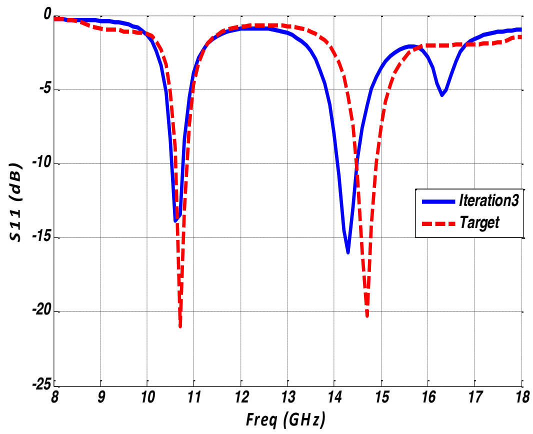
The placement of the feeding port along the center line helps to excite corresponding cavity modes with maximum electric field at the center of the cavity resonator. As a result, TM_{010} and TM_{110} mode are excited in the proposed coaxial-fed SIW cavity resonator antenna. The optimized dimensions of the SIW cavity resonator are chosen such that the two modes resonate at 10.84 GHz and 14.82 GHz to cover X/Ku band applications. The excitation of different modes can be explained with the help of Z_{in} plots extracted from multi-HFSS after embedding the effect of the coaxial feed line as shown in Figure 5.



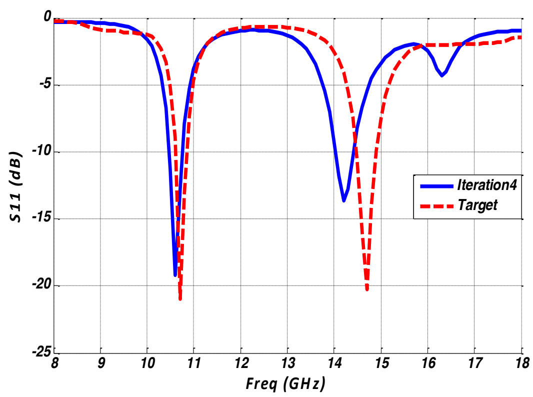
(a) 1st iteration



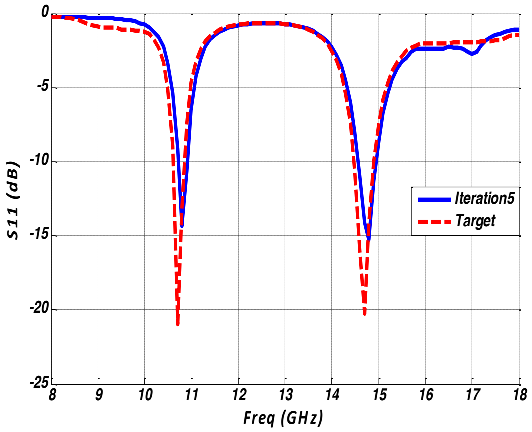
(b) 2nd iteration



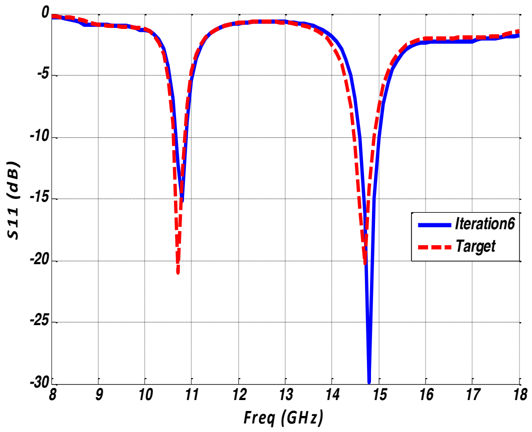
(c) 3rd iteration



(d) 4th iteration



(e) 5th iteration



(f) 6th iteration

Fig. 4. Return loss graph in dual-band X/K bands of the optimized dualband coaxial-fed SIW cavity resonator antenna based ANN modeling

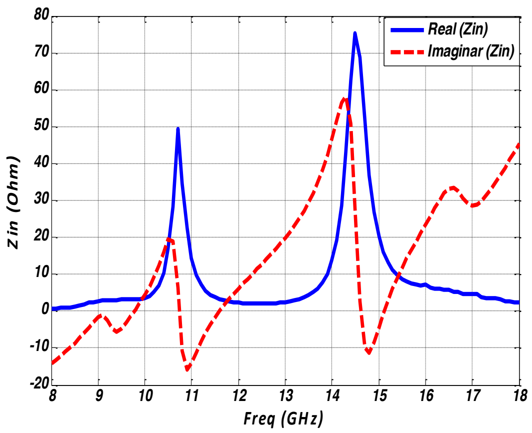
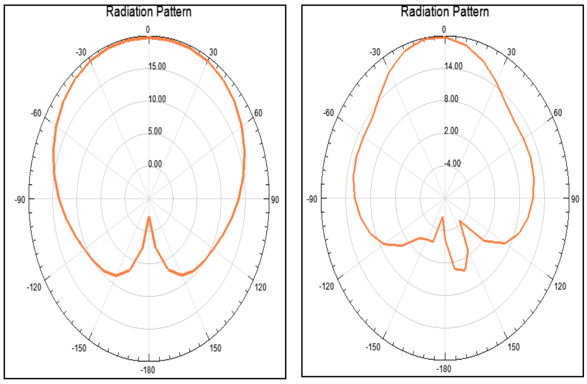


Fig. 5. Real Z_{in}, and imaginary Z_{in} plots of the SIW cavity

Note that the input impedance of the coaxial-fed SIW cavity resonator antenna is well adapted for (Z_{in} = 50Ω). Finally, due to the optimized SIW cavity resonator parameters, the proposed antenna produces unidirectional radiation pattern resulting in a good directivity as shown in Figure 6.

4.4. Equivalent Circuit Model

The coaxial-fed SIW cavity resonator antenna behaviour near to its resonance state is similar to a parallel RLC resonator. The lumped element values of the parallel resonator are calculated using the following set of equations (3)



E-plane H-plane

Fig. 6. Radiation pattern graph of the optimized dualband coaxial-fed SIW cavity resonator antenna

$$\begin{cases} C = \frac{1}{2}\frac{d\,Im\left(Y_{in}\right)}{dw}\Big|_{w=w_0} \\ LCw_0^2 = 1 \\ G = \frac{1}{R} = Re\left(Y_{in}\right)\Big|_{w=w_0} \end{cases} \quad (3)$$

The values of the lumped elements of the parallel RLC resonator presenting the equivalent circuit of the input admittance (Yin=1/Zin) of the optimized dualband coaxial-fed SIW cavity resonator antenna, are listed in Table 4. The proposed equivalent circuit model is shown in Figure 7.

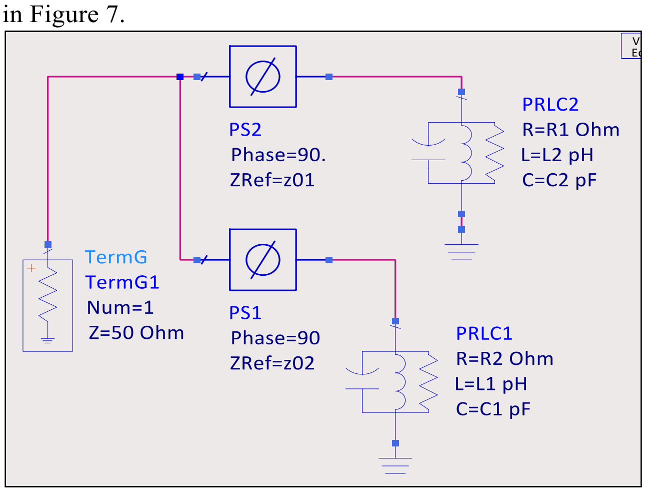


Fig. 7. Equivalent circuit of the optimized dualband coaxial-fed SIW cavity resonator antenna.

Table 4. Geometrical parameters of the equivalent circuit of the optimized dualband coaxial-fed SIW cavity resonator antenna

Parameters	Optimized values
R_1	57.68 Ω
C_1	14.73 pF
L_1	0.0147 nH
R_2	60.52 Ω
C_2	10.7537 pF
L_2	0.01075 nH

Table 5. Optimized parameters of the dualband coaxial-fed SIW cavity resonator antenna using ANN modeling

Parameters	Optimized values (*mm*)
R_1	5.221
R_2	6.511
tx	9.603
ty	9.622
d	0.501

Table 5 shows the final geometric configuration reported from the sixth iteration, selected for the dualband coaxial-fed SIW cavity resonator antenna design after optimization.

Table 6. Comparison of the optimized dualband coaxial-fed SIW cavity resonator antenna to antennas in [15-17]

	Feeding technique: coaxial line					
The optima-zed antenna	**Down band**			**Upper band**		
	f_D	BP_D	Gain	f_U	BP_U	Gain
	10.8	410	4.9	14.8	490	6.2
	Feeding technique: microstrip line					
Antenna in [15]	**Down band**			**Upper band**		
	f_D	BP_D	Gain	f_U	BP_U	Gain
	2.4	409	4.7	2.6	420	4.9
	Feeding technique: SIW cavity					
Antenna in [16]	**Down band**			**Upper band**		
	f_D	BP_D	Gain	f_U	BP_U	Gain
	9.4	134	4.86	16.2	955	6.15
	Feeding technique: coaxial line					
Antenna in [17]	**Down band**			**Upper band**		
	f_D	BP_D	Gain	f_U	BP_U	Gain
	9.4	190	5.3	13.6	200	4.3

ANN model developed for the optimization offers the advantage of superior computational ability to provide optimal geometric configurations due to its high efficiency and interconnectivity to solve design problems. The antenna exhibits high performance for a dual band range from 10.545 GHz to 10.950 GHz, and from 14.55 GHz to 15.0405 GHz, with a bandpass (BP) of 410 MHz (3.81%), and 490 MHz (3.31%), that is much better as compared with the previous designs in [15-17] as demonstrated Table 6.

5. Conclusion

In this paper, a novel dualband coaxial-fed SIW cavity resonator cavity resonator antenna design is proposed for X/Ku band applications by developing an accurate MLP-ANN model and carrying out multiple-HFSS simulations to achieve best approximations to target parameters providing a high structure precision as well as high performance level. About -15dB and -30dB of return losses at approximately 10.84 GHz and 14.82 GHz resonance frequencies have been obtained to be excellent characteristics for the proposed antenna design to operate in X and Ku ranges of frequencies. MPL-ANN model selected for the optimization offers the advantage of superior computational ability to provide an optimal geometric configuration of the dualband coaxial-fed SIW cavity resonator cavity resonator antenna due to its high accordance with user's setting.

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